# CRYOGENIC POWER CONVERSION FEASIBILITY STUDY

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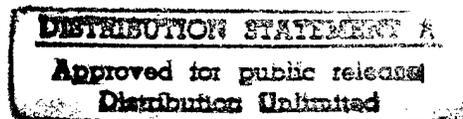
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SECTION 1

INTRODUCTION

Cryogenically cooling power conditioning systems in space-based multi-megawatt power systems will reduce system mass, volume, and complexity. Cryogenically cooled generators and power transmission systems for space are already under development. These generators and transmission busses are considerably lighter and more compact than comparable room temperature components. Most of the mass and volume savings results from the greatly increased electrical conductivity of metals cooled to cryogenic temperatures. Power conditioning components do include metal conductors but also use insulators, semiconductors, and resistors. The behavior of these materials, and thus power conditioning components, is more complex at low temperatures than metals. There is presently no technical data base we can use to predict the behavior of power conditioning systems. It is difficult to predict the mass savings or penalty we must incur if we choose to operate the power conditioning system at cryogenic temperatures.

There is strong incentive, however, to operate the system at cryogenic temperature. Transitioning from the cooled generator to a room temperature converter would cost considerable mass and volume in downleads. There may also be considerable "free" volume that is already at cryogenic temperature within the magnetic shield around the generator.

We see, then, that three questions need to be answered. First, can a power conditioning system be operated at cryogenic temperatures? Second, will we pay a mass or volume penalty for cryogenic operation or will we realize a performance improvement? And third, what needs to be done before we can build a cryogenic power conditioning system?

This report describes a 230 manhour study we undertook to answer those three questions. We reviewed the state of the art in cryogenically cooling typical converter components and materials. We reviewed the properties and hazards of cooling with supercritical hydrogen. Finally, we assessed the ability of WRDC to use small quantities of hydrogen for component development tests. We concluded that almost all power conditioning components can be operated at cryogenic temperatures. We expect cryogenic operation to cause a significant mass and volume reduction for many of the key components. Finally, considerable development work is required before we are ready to build a complete power conditioning system. The following sections detail our study, conclusions, and recommendations.

SECTION 2
POWER CONDITIONING COMPONENTS REVIEW

We reviewed the literature concerning the operation at cryogenic temperatures of every component or material required to build a power conditioning system. In addition to the open literature, we have included some recent results from measurements taken in Dr. Portnoy's lab at Texas Tech University. The components are grouped into Semiconductor Devices, Energy Storage Elements, and Others.

2.1 Semiconductor Devices

Semiconductor devices are used to rectify alternating current and to switch and control power flow. We concentrated on thyristors for controlled switches because they are the only switch component with sufficiently high single device power ratings to consider building a multimegawatt power converter. We also reviewed simple diodes, other semiconductor devices, and more complex integrated circuits.

2.1.1 Thyristors and Diodes

Power thyristors and diodes use essentially the same silicon materials and thus share many physical characteristics even when cooled to cryogenic temperatures. Although much of the detailed behavior with temperature of the physical parameters required to model these components is still unknown, such behavior can be estimated if certain assumptions are made.

Assumptions

1. The devices can be treated as one-dimensional. This is a better assumption for the rectifier than for the thyristor, but steady-state qualitative behavior should not be significantly affected.

2. Contacts are perfectly ohmic at all temperatures. This assumption is probably violated at low temperatures. Ohmic contacts must supply majority carriers at any rate with negligible potential drop across the contact, requiring a high generation-recombination rate and a barrier small with respect to kT/q. At low temperatures, the generation rate decreases substantially and kT/q becomes very small, so that this assumption is probably violated.

3. Impurities are and remain uniformly distributed. This is an abrupt junction approximation, and, even if the diffused distributions more-or-less satisfy this approximation at room temperature, the changes in concentration accompanying

condensation into impurity states differ with concentration, so that the ionized carrier, that is, the free carrier distributions, can be expected to change with temperature.

4.   The minority carrier and ambipolar lifetimes are constant with temperature. Lifetime is strongly affected by temperature, decreasing considerably at low temperatures, so that diffusion lengths will also be affected. However, it is assumed here that the effective diffusion lengths depend only on effective carrier diffusivities.

5.   The effective densities of states, the band gap, and the mobilities are permitted to vary with temperature according to conventional semiconductor theory. Below around 60 K, however, the band gap, $E_G(T)$, remains at 1.17 V ($E_G(0)$) to within 0.2%. (The fermi level is essentially pinned at the donor level, E_{dm} on the n-side and the accepter level, E_a, on the p-side, so that the diffusion potential below this temperature is constant at $E_G(0) - (E_d + E_a)$.) The effective mobilities (and diffusivities and diffusion lengths) are obtained by the combining mobilities (phonon scattering and impurity scattering).

6.   Avalanche breakdown and punch-through voltages are obtained using conventional semiconductor device theory. Forward breakover voltage is calculated from the avalanche breakdown voltage and the small signal gains. These are assumed to vary with temperature through the temperature dependent injection coefficients and transport factors, but are also assumed to saturate at low currents and be independent of current thereafter.

7.   The intrinsic carrier density, ni(T), remains negligible compared with the ionized impurity densities. The calculations employed in the report support that assumption.

We performed calculations for an abrupt junction, one-dimensional n+-p-n--p-p+ thyristor incorporating the following room temperature (300 K) fabrication parameters:

N+-layer (cathode): n+ = 1.5×10^{19} cm^{-3} (phosphorus-doped: Ed=CO.044 eV); tn+ (n+-emitter layer thickness) = 5 μm; minority carrier (p) lifetime - 0.01 μs

p-layer (gating base): p = 4×10^{17} cm^{-3} (aluminum-doped: Ed - C0.057 eV); t_p (p-base layer thickness) = 30 μm; minority carrier lifetime (n) = 0.1 μs.

n--layer (n-base): n- = 9×10^{13} cm^{-3} (phosphorus-doped); Ctn- (n--base layer thickness) = 150 μm; minority carrier lifetime (p) = 5 μs.

p-layer (anode): p = 4×10^{17} cm^{-3} (aluminum-doped); t_p (p-anode layer thickness) = 30 μm; minority carrier lifetime (n) = 0.1 μs.

p+-layer (anode): p+ = 1.5×10^{19} cm^{-3} (aluminum-doped); t_{p+} C(p+-emitter layer thickness) = 5 μm; minority carrier (p) lifetime = 0.01 μs.

The rectifier structure is similar, except that there are no p-bases; that is, the rectifier is an n+-n--p structure. It is assumed in both devices that the temperature independent ambipolar lifetime in the n--base is 1 μs.

Using these values, the avalanche breakdown voltages of the thyristor and rectifier are calculated to be around 2 kV; however, n--base punch-through occurs in the thyristor at somewhat greater than 1.5 kV, so that its effective breakdown voltage is 1.5 kV. This is not its forward blocking voltage, however. Forward breakover will occur at the avalanche breakdown voltage reduced by transistor action in the two equivalent transistors; at room temperature, this is around 1 kV at room temperature. Avalanche occurs in the rectifier approximately at the same time as punch-through; 1.5 kV dropped across 150 μm, the width of the fully depleted n--base, is around 1-- kV per cm, the avalanche voltage in silicon. The avalanche ionization coefficients increase somewhat as the temperature is reduced, so that a lower breakdown field will cause avalanche, and the rectifier avalanche breakdown voltage at a constant depletion width will be reduced; however, the depletion width at low temperatures extends into the p-regions, so that a higher reverse bias is required for a given electric field, and the rectifier reverse breakdown voltage should remain around 1.5 kV even at low temperatures.

The forward voltage drop during conduction in the thyristor is calculated assuming that conductivity modulation occurs in the n--base around room temperature, and in the p-bases below 100 K, where the free hole concentration becomes low enough for conductivity modulation to take place. In the rectifier, conductivity modulation occurs only in the n--base. Heavy conductivity modulation will take place when the current density is around 100 A per cm^2 or greater; this requires an average current rating of 800 to 1000 A (for a 32 to 37 mm device), which is consistent with a 1.5 kV volt thyristor or a 2 kV rectifier.

Figure 1 is a graph of the avalanche breakdown, the punch-through, and the breakover voltages for the thyristor. The thyristor forward blocking voltage is governed by the lowest voltage, forward breakover, which continues to decrease until near 64 K, when it goes through a minimum of around 300 V and begins to increase again, following the avalanche breakdown voltage. It continues to increase until around 43 K, at which temperature punch-through begins to dominate, and the forward blocking voltage begins to decrease again. If the thyristor is to switch any significant voltage, it cannot be used between 40 K and 60 K, when the forward blocking voltage is less than 500 V. This restriction will not apply to the rectifier, for which the reverse blocking voltage should remain near 1500 V down to 20 K. If

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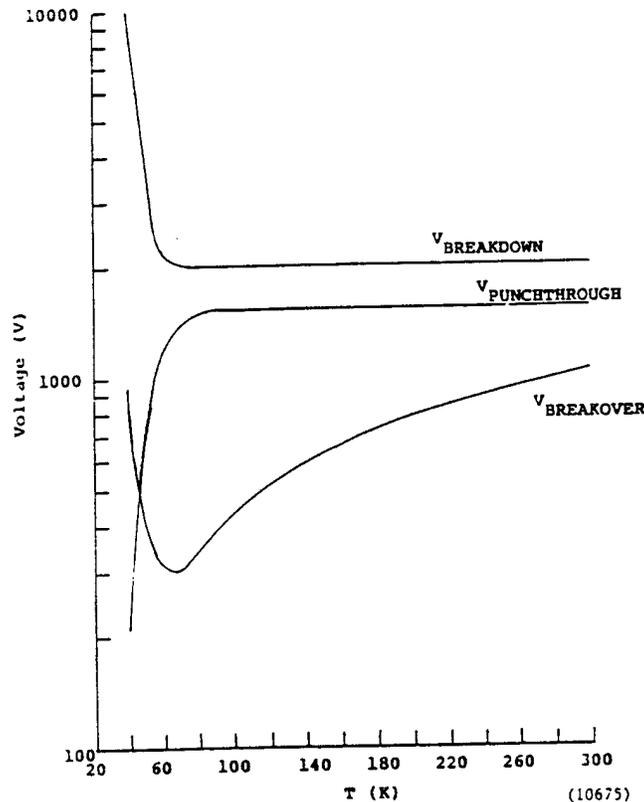
Figure 1.   Avalanche breakdown, punch-through, and forward blocking voltage versus temperature.

Figure 1 is compared with Figure 2, which shows the forward blocking voltage measured locally as a function of temperature for a 1.4 kV thyristor, it can be seen that, at least qualitatively, the agreement is satisfactory.

Figure 3 describes the forward voltage drop during conduction for the thyristor and the rectifier. Both devices behave very similarly in forward conduction, with a voltage near 1 V between 300 K and 100 K, decreasing somewhat between these temperatures. As the temperature continues to decrease, the forward voltage drop is the result of condensation of free carriers in the heavily doped end layers back into the impurity states and the consequent near insulating resistivities of these layers. When this curve is compared with Figure 4, which illustrates the locally measured thyristor forward voltage drop as a function of current and temperature, it is seen that the agreement is not so good. The measured forward drop increases substantially between room temperature and 100 K, and then begins to decrease again. The increase may be attributable to the reduction in ambipolar lifetime as the temperature decreases; this was assumed to be constant in the calculations. The peak and following decrease at 100 K may be the result of conductivity modulation through a wider

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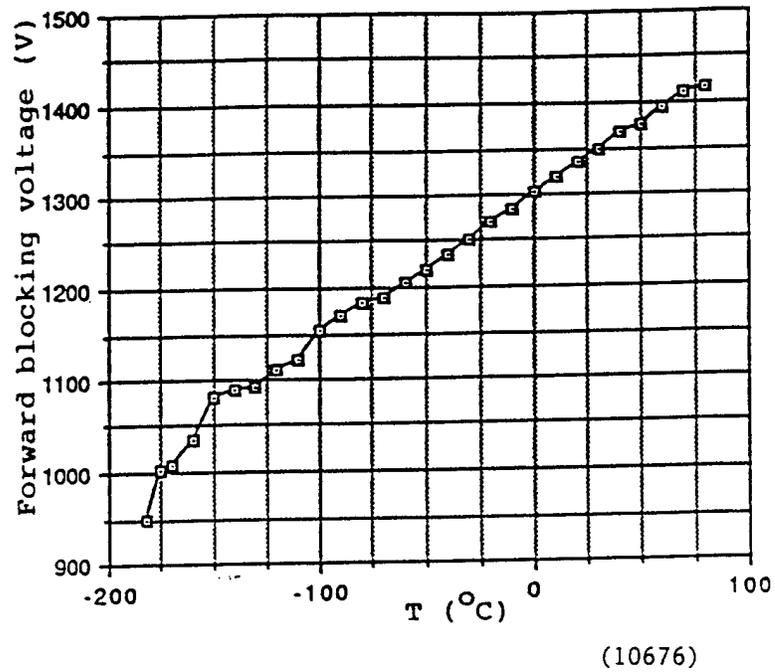
Figure 2.   Measured blocking voltage versus temperature.

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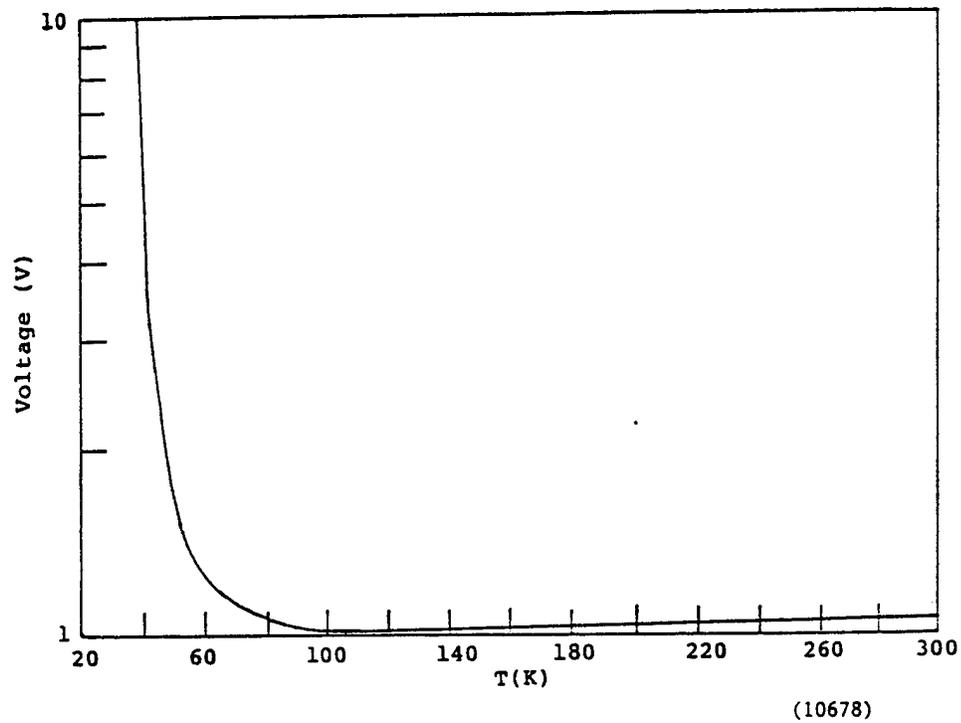
Figure 3.   Forward voltage drop versus temperature.

part of the device, including the end layers, so that the increase in resistivity is compensated by the greatly increased carrier density at low background concentrations introduced by the high current density.
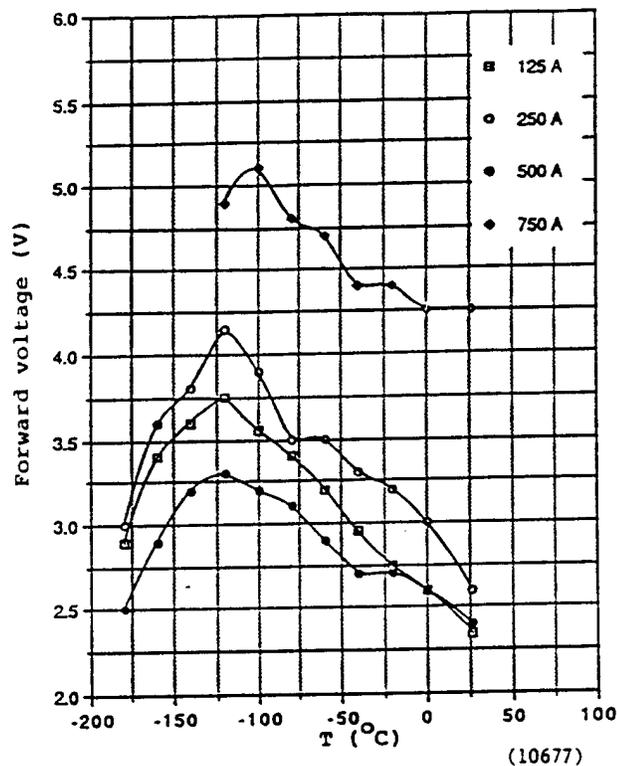
Figure 4.   Measured forward voltage drop versus temperature.

Although no diode measurements have been performed locally, comparison with measurements performed elsewhere indicate much better agreement. The measured diode forward drop remains fairly constant between room temperature and 30 K to 40 K, then increases fairly rapidly until around 10 K, when it saturates. The saturated value of the forward voltage drop is three to six times its room temperature value.

Although the dissipation is increased at cryogenic temperatures because of higher conduction losses, higher dissipation is not necessarily a problem. Acceptable, continuous dissipation at 20 K may be estimated by considering the thermal conductivity of the silicon and the copper anvils, the principal heat conducting elements of a conventional compression (hockey puck) package. At 20 K, the thermal conductivity of silicon is around thirty times its room temperature value, and of copper, around twenty-five times its room temperature value. In that case, a 20 K effective thermal conductivity enhanced some twenty-five times might be expected. The actual rate of heat loss will depend on the steady-state temperature

of the silicon. At 300 K, a normal junction to ambient temperature difference is around 100 K; at 20 K, this would be reduced to perhaps 20 K, so that the net rate of heat transfer would only be a factor of five greater. The permitted power dissipation in either device may be estimated if it is assumed that their cryogenic behaviors are similar (assuming that the thyristor remains functional at 20 K) and that the saturated forward drop at 20 K is 5 V, letting the conduction drop at 300 K be 1 V. In continuous operation, the dissipated power at 1 kA is then 1 kW at 300 k and 5 kW at 20 K. Five times the room temperature dissipation is within reason.

On the other hand, the specific heat of silicon is some 200 times less at 20 K than at 300 K, and of copper, some sixty times less than its value at room temperature, so surge capability will be considerably impaired. For the same permitted adiabatic temperature increase at 300 K and at 20 K, the maximum surge power would be 200 times less at the lower temperature.

It is reasonable to conclude that, whereas the use of thyristors at cryogenic temperatures is at best marginal, high voltage rectifiers are probably useful. Higher heat dissipation caused by greater rectifier losses appears to be manageable, and if the trends observed for thyristors are genuine, low temperature conduction losses may be less than at 300 K. However, the total power handling capability of thyristors (through voltage appears to be badly compromised, and their value as low temperature switches is doubtful.

2.1.2   Other Semiconductor Devices

The following paragraphs briefly describe the primary effects expected when other semiconductor devices are cooled to 77 K. Most of this information is extracted from a paper by Blanchard and Severns.[1]

PN Junction Diodes

Bulk resistance is unaffected by temperature but the offset voltage increases. As the temperature is further decreased, the offset will increase until the diode stops functioning altogether.

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1.   Richard Blanchard and Rudy Severns, "Designing Switched-Mode Power Converters for Very Low Temperature Operation," *Proceedings of Powercon 10*, D-2 Page 1, 1983.

Shottky Barrier Diodes

Bulk resistance decreases and offset voltage increases as temperature is decreased. Forward voltage drop at any current level increases as the temperature is reduced.

Bipolar Transistors

Forward gain is reduced and Collector-Emitter voltage is increased. Thus, performance decreases as the device is cooled.

MOS Power Transistor

On-state gain about doubles as the device is cooled. The on-state resistance decreases by about one half. Breakdown voltage decreases. Device performance thus depends on the circuit application. At moderate working voltages, performance increases.

2.1.3 Integrated Circuits

Integrated circuits include transistors, diodes, resistors, and capacitors. The changes of characteristics for each of these devices do not track together with change in temperature. The IC's operate poorly as the temperature decreases, finally failing to function as designed. The temperature at which an IC ceases to function, and whether the failure is recoverable upon reheating, is circuit dependent.

2.2 Energy Storage Elements

We reviewed the effect of cryocooling most energy storage elements, including capacitors, inductors, and transformers.

2.2.1 Capacitors

We reviewed literature on capacitors at low temperatures. The work can be divided into three technology areas: liquid-dielectric capacitors, conventional electronic capacitors cooled to cryogenic temperatures, and new capacitors designed for cryogenic operation.

Liquid-Dielectric Capacitors

Perfluorocarbon liquid impregnants have vapors with almost the same dielectric strength as the liquid at pressure levels at or above standard atmospheric pressure. Mauldin has used this property to establish an evaporative cooling cycle in the roll without degrading the dielectric strength of the system. This cooling cycle stabilizes the system temperature below

that which causes degradation of the film. Order of magnitude increases in capacitor life have been recorded for a given stress level.[2] Cooling the can from 35 down to 18 °C also improves life by an order of magnitude.

This system suggests that H_2 might perform the same function as perfluorocarbons, but at temperatures around 20 K. H_2 is an excellent dielectric in terms of dielectric strength and loss. Dielectric constant is only 1.24, though. Boiling the liquid seems to have no effect on the breakdown voltage. Freezing the liquid approximately doubles the dielectric strength from 745 to 1340 kV/cm. Loss tangents are so low as to be generally unmeasurable.

Dielectrics (fluids) typically used in capacitors have high dielectric constants (e.g., 3.6, 6.9, 10.0). This implies that the H_2 insulated capacitor might be big/heavy since the dielectric constant of H_2 is only 1.2, unless strong advantage in breakdown strength is gained.

Mathes and Minnich investigated the use of ferroelectric fluids as dielectrics in capacitors.[3] Using liquid nitrogen and some silicon fluids as impregnants, dielectric constants as high as 80 were measured. Dielectric strengths were disappointing but the authors hoped to reach 2500 volts/mil with a relative dielectric constant of about 40. The resulting energy density could theoretically reach 60 J/cu in. (3.7 J/cc). This is about what Dr. Lawless has already achieved.[4] Note that Dr. Lawless' dielectric is of much higher permittivity but must be of much lower dielectric strength.

Conventional Electronics Capacitors Cooled to Cryogenic Temperatures

Many types of capacitors, including film, mica, and tantalum, can be cooled to cryogenic temperatures with no change in capacitance.[1] Lower temperatures should result in lower equivalent series resistance (ESR), increased dielectric strength, and increased thermal conductivity. (Note that Blanchard and Severns are only making an educated guess about these properties where capacitance was actually measured for the seven types of capacitors shown in Table 1.) Blanchard and Severns postulate that cryogenic operation of capacitors

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2. G. H. Mauldin, W. C. Nunnally, M. C. Thompson, and W. J. Sargeant, "The Performance of the Perfluorocarbon Liquid/Plastic Film Capacitor Technology in Repetitive Discharge Pulse Power Service," 4th IEEE Pulsed Power Conference, Albuquerque NM, June 1983.

3. K. N. Mathes and S. H. Minnich, "Cryogenic Capacitor Investigation," Contract Number NAS8-20617, May 1967.

4. W. N. Lawless, "Unsolicited Proposal in Capacitive Energy Storage at Cryogenic Temperatures," CeramPhysics, Inc., Westerville OH.

will pose no problems and should result in higher power handling capability with lower losses. Specific energy should also increase.

TABLE 1. MEASURED CAPACITANCE AT ROOM AND CRYOGENIC TEMPERATURES

TYPE	MANF	Value (μF)		
		300° K	77° K	4.2° K
Ceramic	Corning	1.036 1.001	0.457 0.451	0.387 0.374
Mica	Elmenco	1.002 0.997	0.997 0.993	0.990 0.990
Film (polysulfone)	S & EI	9.923 9.955	9.452 9.552	0.309 9.444
Film (polysulfone)	S & EI	1.195 1.246	1.126 1.176	1.115 1.161
Film (polysulfone)	S & EI	1.017 1.099	1.012 1.035	1.009 1.027
Film (polycarbonate)	S & EI	1.221 1.233	1.166 1.170	1.155 1.158
Tantalum	Kemet	1.045 0.998	0.973 0.909	0.936 0.854

We, however, are concerned about the mechanical properties of cryocooling commercial capacitors. Also, most high-voltage energy storage capacitors are oil-impregnated. These capacitors are clearly not suitable for cryogenic operation.

We believe that capacitors are not a cryogenic power system *problem*. The new capacitors designed specifically for cryogenic operation may even be lighter, smaller, and more reliable than room-temperature capacitors.

New Capacitors Designed for Cryogenic Operation

Researchers at Duke university have studied thin film capacitors using silicon oxide and bismuth trioxide at cryogenic temperatures.[5] They paid particular attention to SiO with zirconium because there is an interaction between the SiO and Zr. Effective, useful capacitors were made with dielectrics of 4000 Å thickness and tested from 300 to 4.2 K

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5. "Final Technical Report on a Study of Thin Film Dielectrics and Insulators for Cryogenic Applications," Department of Electrical Engineering, Duke University, Durham NC, under Contract Number DAAK02-70-C-0110, August 1971.

Capacitance and dissipation were unaffected by operating temperature and the capacitors survived several thermal cycles from 300 to 4.2 K and back.

The interaction between the SiO and Zr results in non-linear volt-ampere characteristics including voltage switching much like a diac. We doubt this phenomenon is of use for energy storage capacitors.

No voltage breakdown tests were reported (or made?) so energy density information is unavailable.

Dr. Lawless at CeramPhysics has demonstrated energy storage densities of 6 J/cc.[6] Density is not mentioned, but we estimate the density of a ceramic capacitor to be between 2700 and 6500 kg/m^3. This means Lawless has demonstrated capacitors storing energy at least 1 and maybe 2 kJ/kg. This is quite impressive as the industry is selling 0.1 kJ/kg and only promising 0.3 kJ/kg for the near future.

Note that these capacitors have been made, assembled into banks, and cycled 100,000 times. Note also that these caps are operated at 77 K to enhance permittivity and dielectric strength and reduce losses. The technology (material and/or manufacturing) is patented. The materials actually have a peak in their dielectric constant at 77 K of 7,000 to 10,000.

Lawless believes improvements are possible with improved manufacturing techniques. Specifically, he proposes to use Rate-Controlled-Sintering (RCS) to improve the density of the dielectric and to control grain size (he believes extremely fine grains will have better reliability with respect to voltage breakdown). In a phone conversation with Dr. Lawless, he told us he expected RCS to possibly double the dielectric strength in the capacitors. We think we can expect the technology to be limited to 2 or maybe 4 kJ/kg.

2.2.2   Inductors

Inductors are used to shape pulses, store energy for pulsed power, and filter signals. Inductors are generally classified as either iron-cored or non iron-cored. We reviewed the effect of cryocooling on both types of inductors.

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6.   C. F. Clark, "Capacitive Energy Storage at Cryogenic Temperatures," AFOSR-TR-87-0327, Contract Number F49620-86-C-0029, January 1987.

Iron-Cored Inductors

Iron-cored refers to any inductor which uses a core material with a relative magnetic permeability significantly greater than one. More common than "iron" in modern inductors is ferrite and nickle-iron (Ni-Fe).

The saturation flux for ferromagnetic materials increases from 5 to 20 per cent as temperature is lowered form room temperature to absolute zero. Relative permeability is essentially unchanged for nickle-irons but drops by factors of ten or more for ferrites.

Core losses increase as temperature is decreased. The increase is due to increased conductivity (eddy current losses) and increased hysteresis losses. The increased loss is dramatic for ferrites but barely discernible for Ni-Fe.

The mass of an inductor is equal to the sum of the core mass plus the winding mass. We might expect that the inductor mass is not significantly affected by cooling since the magnetic properties of the core material are essentially unaffected by cooling. Closer examination shows, however, that we can expect inductor mass to decrease by about four times when cooled to 20 K.

At room temperature, a minimum mass inductor places about half the mass in winding conductor and half in core material. Figure 5 shows a simple representation of such an inductor. The mean length of each turn in the winding is about the same as the length of the mean flux path around the core. The total cross-sectional area of the winding is also about the same as the cross-sectional area of the core.

The winding conductivity will increase by at least 100 times when the conductor is cooled to 20 K. The total cross-section of the winding will thus be reduced by at least 100 times for the same core flux level (in Ampere-turns). The core cross-section can not be decreased since it is proportional to the flux. The core length can, however be decreased. The core length must be sufficient to form a closed path around the winding. Now that the winding cross-section is essentially zero, the flux path around the conductor can be decreased substantially. A first order approximation of this decrease can be evaluated by examining the following geometry.

First, assume the core is a torus of minor radius r and major radius 2 r. The winding makes up the same size torus as shown in Figure 6. Now, reduce the total winding cross-section by 100 times. The major radius of the core can now be reduced to about r. Figure 7 shows the resulting geometry.
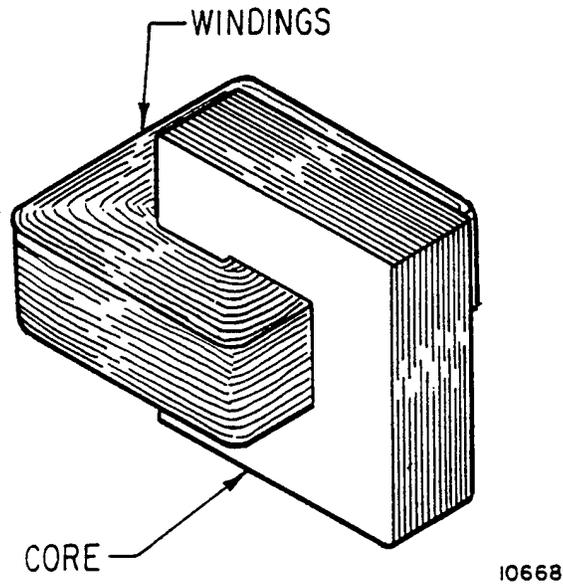
Figure 5.   A minimum mass inductor is about one-half core material and one-half conductor.
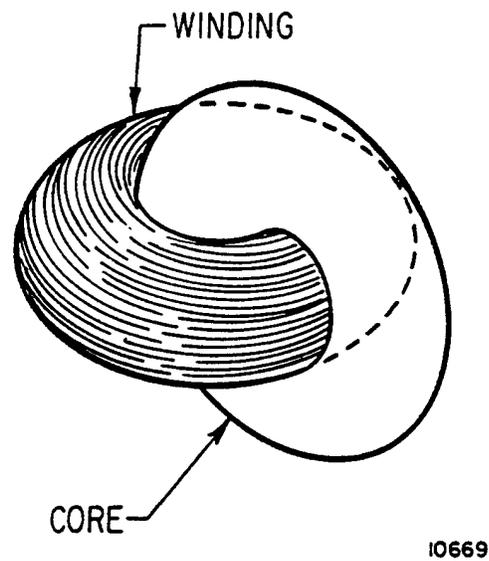
Figure 6.   A two-torus inductor.

The volume of the core is reduced by a factor of two, so the core mass is also reduced by a factor of two. The conductor mass is reduced to essentially zero as compared to the new inductor mass. The total mass of the inductor is thus reduced by a total of four times when cooled from room temperature to 20 K.

REDUCED CORE LENGTH⌐

REDUCED WINDING
CROSS SECTION
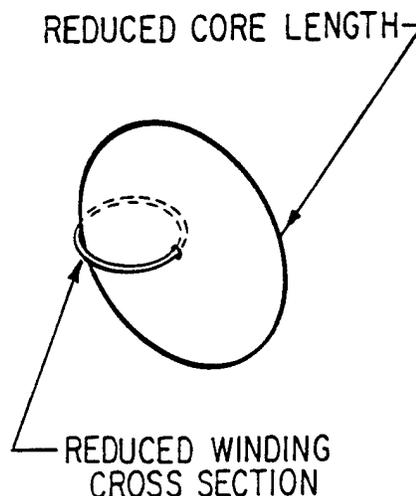
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Figure 7.   A two-torus inductor after the winding cross-section is reduced by 100 times.

In summary, we expect the mass of an iron-cored inductor to decrease by about four times when compared to a room temperature minimum mass design. This decrease depends on using hyperconductor or high-purity aluminum windings. The estimate is based on little change in core properties with temperature and a very simple geometry. It is clear, though, that no mass penalty must be paid for cooling the inductor, and some decrease in mass can be achieved through careful design.

Air-Cored Inductors

In an air-cored inductor, the principal mass component is the conductor itself. The conductor mass depends on the inductance, resistance, energy stored, and the acceptable heating during the current pulse. Cooling hyperconductor to 20 K decreases the resistance be at least 100 times. Any mass decrease depends on which parameter controls the mass at room temperature. If the room temperature mass is constrained by winding stress, that is, the stored energy, then cooling the inductor will not allow the mass to be reduced. The resistance is decreased so the inductor performance increases, but the mass does not decrease.

We find that most room-temperature inductor designs are resistance-constrained rather than stress-constrained. Thus, cooling the inductor does allow the mass to be reduced considerably. The conductivity of hyperconductor changes so much with temperature that most designs we've studied become stress constrained at 20 K. That is, a minimum mass design at room temperature usually depends on the allowable resistance. A minimum mass design at 20 K depends on the maximum allowable stress in the winding. An inductor designed for 20 K operation is generally ten to twenty times lighter than an inductor having

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the same specifications but designed to operate at room temperature.

2.2.3   Transformers

Transformers are simply two or more closely coupled inductors. The effect of cooling a transformer is therefore essentially the same as cooling an inductor. This generalization applies to both air-cored and iron-cored transformers.

We therefore expect cryocooling to improve transformer performance. Efficiency will increase and mass will decrease. Maximum mass decrease for an iron-cored transformer will be about four times. Air-cored transformer mass will decrease by ten to twenty times. These predictions assume the transformer is wound with hyperconducting or high-purity aluminum windings.

2.3 Other Components and Materials

We reviewed other power system components and materials including conductors, insulators, resistors, and varistors. Section 3 provides additional information on dielectrics and conductors.

2.3.1   Conductors

Conductivity of the conductors such as wires in transformers increases by about a factor of ten when the temperature is lowered from room temperature to 80 K. The skin depth decreases with increasing conductivity so the overall reduction in resistive losses for a conductor cooled to 80 K is reduced to about three times.

Cooling high-purity aluminum to 20 K improves the conductivity by a factor of 100 to 1000. Again, the skin-depth problem will limit the reduction of resistive losses to 10 to 30 times for high-frequency or pulsed conductors.

2.3.2   Insulators

The net effect of cryogenic temperatures on plastic insulations is to increase the dielectric strength at the expense of the mechanical properties. The dielectric strength of Kapton film, for example, almost doubles when the film is cooled from 400 K to cryogenic temperatures.

The main problem with insulations is that they become brittle when cooled. The second problem is that the coefficient of thermal expansion is so different between most plastics and most metals. High stresses occur whenever the package is cooled. These stresses

combined with the increased brittleness of the plastics often results in cracks in the insulation and, of course, insulation failure.

2.3.3   Resistors

Resistors are generally used in control functions in the electronics circuits.   Most resistors work fine at cryogenic temperatures excepting the common carbon composition type.[1]

2.3.4   Varistors

Some research has shown that many varistor materials do not show "varistor behavior" at cryogenic temperatures.[8] We have been informed by Thibodeaux, who has reviewed this data, that these early reports were wrong. Most varistor materials perform satisfactorily at cryogenic temperatures.

Data for Zinc-Oxide varistors may be typical. The total enthalpy of the material doubles when cooled to 77 K. Thus the peak energy rating for a single pulse should double if the device is cooled to 77 K or below. Note that this energy would heat the device to a final temperature of about 400 K. Considerable time would be needed to cool the device down for the next pulse.

Equally encouraging is that the thermal conductivity of Zinc-Oxide peaks at about 80 K. Although thermal conductivity decreases below 80 K, the conductivity at 20 K is still as high as the room temperature value. This means that we can expect the average power rating of varistors to increase as they are cooled. We can not make quantitative predictions because very little information about room-temperature power ratings is available. (Varistors are presently used almost exclusively for non-repetitive surge protection.)

2.4   General Thermal Characteristics of Power Components

The ability of electronic components to dissipate heat at very low temperatures is considerable enhanced. The enhancement occurs because the temperature drop to the ambient can be larger and because the thermal conductivity of silicon and many metals is better at low temperature than at room temperature. It is fortunate that the thermal conductivity of silicon peaks at about 30 K where the conductivity is 40 or 50 times greater than at room

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8.   Rene J. Thibodeaux, "Physics of Zinc-Oxide Cryovaristors in High Power Switching Applications," IEEE, CH2662-5/88/0000-0288, 1988.

temperature.

2.5 Component Reliability

Thermally activated mechanisms are responsible for one class of failure mechanisms in semiconductors. Therefore, reducing the operating temperature to LN_2 or LHe levels significantly increases device lifetime when it is limited by thermally activated mechanisms.

Reducing operating temperature will increase mechanical stress caused by differential expansion rates and cause a new class of failures. The total differential expansion from room temperature to cryogenic temperatures is several times greater than the differential expansion that typically occurs from room temperature to 125° C operation. Mechanical package design problems have always plagued semiconductor designers. We believe designers would experience even greater problems when forced to design for cryogenic to room temperature cycling.

2.6 Power Components Summary

Most power components will function at liquid nitrogen or liquid oxygen temperature. Most will have slightly different characteristics at these temperatures than at liquid nitrogen temperatures. A circuit designed to operate at 77 K must be designed specifically to operate at that temperature. One designed to operate at room temperature cannot simply be cooled and expect to function at cryogenic temperatures.

Semiconductor operation at 20 K is more difficult to predict. Very little information is available and virtually none has been experimentally checked. It is known that many semiconductor devices will fail to operate at some temperature because charge carriers will "freeze out". The performance of all semiconductor devices needs to be predicted down to this minimum temperature. The performance must be experimentally checked because performance is increasingly difficult to predict as temperature decreases.

Simple components like conductors, resistors, inductors, and capacitors will generally function well at 77 K and 20 K. In any component in which conductor mass is significant, considerable mass and volume reduction can be achieved by cooling. Thus, non-iron-cored inductors and transformers will be much lighter and smaller when cooled to 20 K. Iron-cored devices will be about one quarter the weight and volume of similarly-rated room-temperature devices.

One of the only technologies we reviewed which has *demonstrated* tremendous improvement over the best available room-temperature technology was the cryogenic

capacitors designed by CeramPhysics. These capacitors have already demonstrated better specific energy than the best commercially available energy storage capacitors.

A tremendous amount of information is required to design an efficient, lightweight, reliable electronic circuit. Electrical and thermal characteristics must be known accurately for every component. These characteristics must be known as a function of operating temperature and often voltage. No such information is presently available for cryogenic temperatures. Some physics has been predicted but extremely little information has been experimentally checked. Accurate predictions are impossible for semiconductors. The material characteristics are nonlinear and many of the characteristics have opposing trends with temperature.

The first step to designing cryogenically-cooled power conditioning circuits is to accurately characterize the needed devices at temperatures down to at least 20 K. There will be the potential to improve the performance of many devices by specifically designing them for cryogenic operation. First, though, we must develop the design data base for existing components.

SECTION 3

HYDROGEN-COOLED CRYOPOWER SYSTEMS

3.1   Introduction - Cryopower Systems

The reasons for operating power systems at cryogenic temperatures are to save power and to reduce mass by reducing ohmic power losses. Cryopower systems fall into two classes: superconductive or cryoresistive.   There is no steady-state power dissipation in superconductors.   Present superconductive systems are mostly high field DC magnets and typically operate in a liquid helium environment at 2 to 5 K.   There are no further electric power requirements, once the magnetic field has been established, except keeping the system cold.   The high temperature superconductors discovered in 1986 may some day be usable up to liquid nitrogen temperatures (77 K), but so far have not been produced in bulk form with usable current densities.

The largest energy influx into the superconductive system is usually along the power leads and results in a heat load of 2 to 5 frigi-watts/kA for a pair of leads.   This translates into a boil-off of 2 to 5 liters/hour of liquid helium.   Current leads for 1 kA, cooled by helium boil-off gas, are available commercially and 10 kA leads have been designed and used by the author.   50 kA presents an upper limit for helium usage.   After the design of the device itself, the main engineering problems in superconductive systems are insulation and energy losses attributable to the leads.

Cryoresistive, sometimes called hyperconductive, systems use the fact that the resistivity of all pure metals drops by a factor of about eight (8), when they are cooled from room temperature (300 K) to liquid nitrogen (77 K), and by a factor of 100 or 1000 at liquid hydrogen (20 K).   The resistivity levels off at low temperatures.   The limiting Residual Resistivity Ratio (RRR) depends critically on metal purity, both chemical and physical. Straining increases resistivity.   The higher the RRR, the narrower the "headroom" available above 20 K.   The primary engineering concern in cryoresistive systems is heat transfer.

The heat influx from the leads into a cryoresistive system is of little importance for two reasons:
(a)   The same number of frigi-watts translates into an order of magnitude lower boil-off of liters of liquid hydrogen, and
(b)   Other sources of power dissipation are larger by three or more orders of magnitude.

The author designed and operated 10 kA leads in a 8 T, 20 kW liquid hydrogen cooled electromagnet 30 years ago.   Their weight was less than 2 kg.   The only concern is avoiding

burnout.

If the power costs of refrigeration are included in the balance sheet, overall power savings in cryoresistive systems are less dramatic than implied by the possible resistance ratios. Table 2 indicates the net reductions after allowing for the Carnot factor and the limited mechanical efficiency of the refrigerator. On the other hand, when "free" refrigeration is available, as may be the case in some space missions, the resistance ratio alone will be the relevant figure of merit.

TABLE 2.   REFRIGERATION ECONOMICS

	Temperature (K)				
	4	14	20	20	77
Resistance Ratio	10,000	5000	1000	100	8
Carnot Factor	74	20	14	14	2.9
Mechan. Effic.	0.15	0.2	0.3	0.3	0.4
Possible Gain	20	50	21	2.1	1.1

3.2 Background Information - Cryogenics

The primary reason for choosing to operate any fluid-cooled cryogenic system at supercritical conditions is to have single-phase heat transfer. There can be no phase separation (bubbles) in this heat transfer regime and heat transfer can be calculated by standard engineering methods (Dittus-Boelter). The drawbacks are that system pressures will have to be above the critical pressure, which can be quite high (but not for $1H2$), and that the coolant temperature is not constant, but increases as thermal energy is taken up in the specific heat of the fluid. (By contrast, a boiling, or two-phase cooling temperature is simply fixed by the local pressure at any point in the system.)

A secondary advantage of the absence of bubbles in electrical systems is the avoidance of the local enhancement of the potential gradient, caused by variations in the dielectric constant.

3.3 Background Information - Dielectrics

The dielectric strength of any material is never a simple physical constant, but rather an engineering limit based on statistically scattered data. The reason for this is that electric breakdown is a complex chain of events that is influenced by geometry, physics, chemistry,

system size, time and cosmic rays or other sources of ionization and includes such processes as ion multiplication, corona, and streamers.

Geometry and surface roughness of the electrodes affect the potential gradient, even in the absence of obvious stress raisers, such as sharp points or corners. In a composite dielectric constant of the material, so that, as mentioned earlier, the presence of minute inhomogeneities, such as flaws or bubbles, as well as transitions between different dielectrics, can produce local enhancement and breakdown.

The chemistry of the broken down material and any atmosphere present during breakdown may raise or lower subsequent breakdown voltages by smoothing or cleaning the surface, or by leaving decomposition products, such as carbon.

System size affects the observed strength and is usually represented through Weibul statistics. Short and longtime DC results may differ and then again differ from AC values, which themselves are frequency dependent, and different yet from impulse results.

3.4 Physical Properties of Hydrogen

Hydrogen has two molecular forms, designated as ortho or para, depending on whether the two atoms in the molecule have parallel or antiparallel nuclear spins. Both forms are usually present. Their equilibrium ratio varies from 75% ortho at room temperature, to 50% para at 77 K, and 99.8% para at 20.4 K. Some properties of liquid hydrogen, such as vapor pressure and the normal boiling point, differ significantly for different o- and p- contents. Freshly liquefied hydrogen only slowly converts from the "normal" room temperature composition, releasing 527 kJ/kg (of ortho), sufficient to boil off almost 80% of the mixture. The presence of a catalyst in commercial liquefiers guarantees the delivery of at least 95% p-H2, which greatly reduces the loss of stored liquid.

Information on the physical properties of liquid and gaseous hydrogen from the freezing liquid line to 3000 K and at pressures of up to 100 MPa has been compiled, smoothed by computer to be thermodynamically consistent, and tabulated in NBS Monograph 168.[8] The monograph also includes combustion and safety data and represents the legacy from over 25 years' effort by the NBS Cryogenics Engineering Laboratory at Boulder. To use these data in an engineering design project, one only has to decide on how supercritical the system will be and on how large a temperature differential will be utilized

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8. Selected Properties of Hydrogen (Engineering Design Data), R. D. McCarty, J. Hord, and H. M. Roder, NBS Monograph 168, USGPO Feb. 1981.

for heat transfer.

Table 3 lists some of the relevant "standard" cryogenic properties, at saturated vapor pressure, for 22.4 K equilibrium liquid, which is 99.8% para.

TABLE 3. SATURATED 22.4 K EQUIL LIQUID (99.8% para)

Triple Point Temperature	13.80 K
Triple Point Pressure	0.007 MPa
Normal Boiling Point	20.26 K
Critical Temperature	32.98 K
Critical Pressure	1.293 MPa
Density @ 20.3 K	70.8 kg/m^3
Specific Heat	9.7kJ/kg·K
Heat of Vaporization	446 kJ/kg
Thermal Conductivity	99 mW/m·K
Dielectric Constant	1.230
Electrical Conductivity	nil
Dielectric Strength	30 MV/m @ 0.1 MPa
	69 MV/m @ 0.5 MPa
Dielectric Loss Tangent	10^{-4} @ 10 MV/m (rms)
	3×10^{-4} @ 15 MV/m (rms)

The electrical conductivity of liquid hydrogen (in the absence of tritium contamination) is negligible. As a matter of fact, the observed current is voltage independent, as would be caused by the natural radiation background. The dielectric strength for liquid hydrogen has been measured by Jefferies and Mathes[9] and by others,[10] as referenced in NBS Monograph 168.[8]

The breakdown in gaseous hydrogen follows the Paschen law over a wide range of pressures and temperatures, including cryogenic ones. The minimum breakdown voltage has been observed as about 250 to 300 V for a distance-density product of 10×10^{-7} g/cm^2 (10×10^{-6} kg/m^2)

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9. M. J. Jefferies and K. N. Mathes, "Dielectric Loss and Voltage Breakdown in Liquid Nitrogen and Hydrogen," IEEE Trans EI 5, 83-91 (1970).

10. J. Gerhold, "Dielectric Breakdown of Cryogenic Gases and Liquids," Cryogenics 19, 571-584 (1979).

The measurements on dielectric loss[9] show a rather large and unexpected field dependence, as well as variations with time during the experimental observations.

Appendix A is a photocopy of a part of the massive tables in the previously mentioned NBS monograph at the critical isobar of 1.293 MPa. Appendix B is from the next entry at 1.5 MPa. Table 4 excerpts and rounds off some entries from these appendices. It is apparent that, within the given pressure-temperature region, the temperature change from 20 to 25 K has a much greater effect on the numbers than the pressure change from 1.3 to 1.5 MPa.

TABLE 4. CRITICAL AND SUPERCRITICAL PROPERTIES

Pressure	1.3		1.5	
Temperature (K)	20	25	20	25
Enthalpy (kJ/kg)	-247	-195	-245	-193
C_p (kJ/kg·K)	9.1	12.3	9.0	12.1
Density (kg/m³)	72.6	66.6	72.9	67.0
Thermal Cond. (W/m·K) x $10x10^7$	102	105	102	106
Viscosity (kg/m·s) x $10x10^7$	146	103	148	104
Dielectric Constant	1.236	1.215	1.237	1.217
Prandtl Number	1.30	1.20	1.30	1.19

We are not aware of any experimental data on dielectric strength and losses for supercritical fluid. It is probably safe to assume the pressurized liquid value of 70 MV/m for design purposes. As mentioned, the loss data for liquid are somewhat strange and possibly suspect, but could be used to set an upper limit to define possible extra cooling needs.

SECTION 4

TESTING WITH SUPERCRITICAL HYDROGEN AT WRDC

The hazards of experimenting or operating with superfluid hydrogen at pressures of 1.3 to 1.5 MPa (13 to 15 atm, or 176 to 206 psig) are only sightly greater than using liquid hydrogen at atmospheric pressure. As long as the equipment is properly designed (ASME Code for Unfired Pressure Vessels, Sec. VII), there should be no additional problem areas. As a matter of fact, the problem of air-inleak due to pressure, is eliminated.

Hydrogen embrittlement generally does not occur with face-centered cubic metals or alloys, as long as they are not strained to the yield point. Copper, 316 stainless steel and 5000 and 6000 series aluminum alloys are good choices. Body centered and hexagonal metals are undesirable. Even with materials that embrittle, there is no hydrogen diffusion into the metal at the cryogenic temperatures. The embrittlement only occurs when H2 gas is in contact with metal between 150 and 400 K. On the other hand, flashover would cause local heating and even dissociate H2 into rather reactive free radicals, so that there could be some "chemical" deterioration of electrodes or other parts subject to arcing. Fortunately, the mass of activated H2 would be small.

Flashcover can be more of a problem for solid dielectrics in the cryogenic environment. The choice of solid dielectrics depends on voltage, but is probably limited to ceramics or simple hydrocarbon polymers above 20 kV.

4.1 Supercritical Heat Transfer

The analysis of supercritical heat transfer is not difficult, but uses dimensional analysis which requires an iterative procedure based on the Dittus-Boelter relation:

$$Nu = K \cdot Re^{0.8} \cdot Pr^{0.4}, \tag{1}$$

where

Nu =   Nusselt Number = $h\, D_1 / k$

Re =   Reynolds Number = $D\, v\, dens / \mu$

Pr =   Prandtl Number = $C_p\, \mu / k$

A =   area of heat transfer

C_p =   heat capacity at constant pressure

D_1 =   a characteristic dimension of object being cooled

K =   0.023

$\dot{Q}$ = energy transfer

T_1 = temperature of flowing coolant

T_2 = temperature of cooled surface

dens = fluid density

h = heat transfer coefficient at cooled surface = $\dot{Q}/\{A\cdot(T_2-T_1)\}$

k = thermal conductivity

μ = viscosity

v = fluid velocity

Clearly a number of iterations will be required to adjust the flow velocity, to vary the Reynolds number, to achieve the required heat transfer, and to limit the temperature excursion of the cooled object. There are computer programs to do all this, but we do not at present have access to them.

4.2 System Design

The usual cryogenic engineering problem of avoiding mismatches in thermal contraction will have to be faced in all systems. By contrast, ceramics will contract much less than most metals, typically a factor of three less, whereas unfilled polymers contract by a factor of three more than metals. Reinforced or filled polymers can be designed to match most metals.

Cryoelectrical power equipment always requires a major transition between ambient and cryogenic temperatures, that is connected while the power is ON, and a "minor" connection for cooling purposes, which may be intermittent. In addition, the cryogenic environment has to be completely surrounded by thermal insulation and sealed against the atmosphere. This places additional constraints on the means of achieving electrical insulation. There can be no "free" air insulation at terminals, or a little bit of corona to smooth out voltage gradients. The only electrical equipment with similar configurations may serve as models for our design.

Design A would have a removable can, with the current leads relatively close together on a single lid and with he test equipment suspended from the lid. For this topology, the avoidance of the usual cryogenic frosting of the leads becomes of paramount importance. The control and direction of internal gas flows is not trivial, and potential gradients are likely to be quite non-uniform.

Design B, a straight through tubular assembly, is applicable primarily to 2-lead DC or single-phase AC equipment, where one lead can be grounded. Flow and flow velocities, which are essential to heat transfer from the supercritical fluid, are more easily controlled. Potential gradients can be more uniform and probably lower, especially if the dewar can be

make from FRP materials. The only drawbacks are that provision has to be made for the thermal contraction of the long inner container and its contents, relative to the outer container, and that at least one large demountable cold vacuum seal (of the diameter of the experimental arrangement) has to be provided.

For a given power transfer, there is a trade-off between accepting the added refrigeration costs at high currents and low voltages and "fighting" the high voltage insulation problem. However, as mentioned in the introduction, for all but superconducting systems, lead refrigeration is only a part of the total refrigeration load, so that high current low impedance designs will be favored.

In general, voltage insulation can be divided into three regimes:

a) the region up to 10 kV, which permits all kinds of dielectrics and simply machined surfaces,

b) the region between 10 and 50 kV, where corona discharge from sharp points and corners and surface tracking have to be considered, and

c) the region from 50 to 200 kV, where totally different procedures and technology are required.

The conceptual design of a 10 MW continuous single-phase cryoresistive system, operating at 20 K, will be used to clarify some of these precepts. Table II tells us that this system would boil off 22.4 kg or 0.317 m³ (317 liters) of liquid hydrogen per second. This is about 10% of the mass flow associated with a rocket test and clearly requires that kind of test facility. The author has vented up to 3 liters per second from a non-flared stack at Los Alamos 30 years ago. The corresponding power of about 100 kW really represents the upper limit of what can and should be done in general purpose facility. Anything larger requires a remote test site with an exclusion radius of hundreds of meters (see below).

Current leads can easily be designed for 1 or 10 kA. Their power losses of 5 or 50 watts are negligible, even in a 100 kW system. There are no incentives to run cryoelectric systems at currents of less than 500 or 1000 A. Maximum system voltage would thus be 10 kV for the 10 MW system at 1 kA and falls in the "easy" range. Operation at higher voltages would only be justified to develop technology rather than near-term tests of equipment.

4.3 HYDROGEN-COOLED TESTING AT WRDC

NBS Monograph 168[8] gives quantity graphs for personnel and property protection near unbarricaded liquid hydrogen storage and experimental areas (Figure 8), for dewar separation (Figure 9), and for general industrial storage standards (Figure 10). These figures exhibit the range of conservatism applied by different authorities.
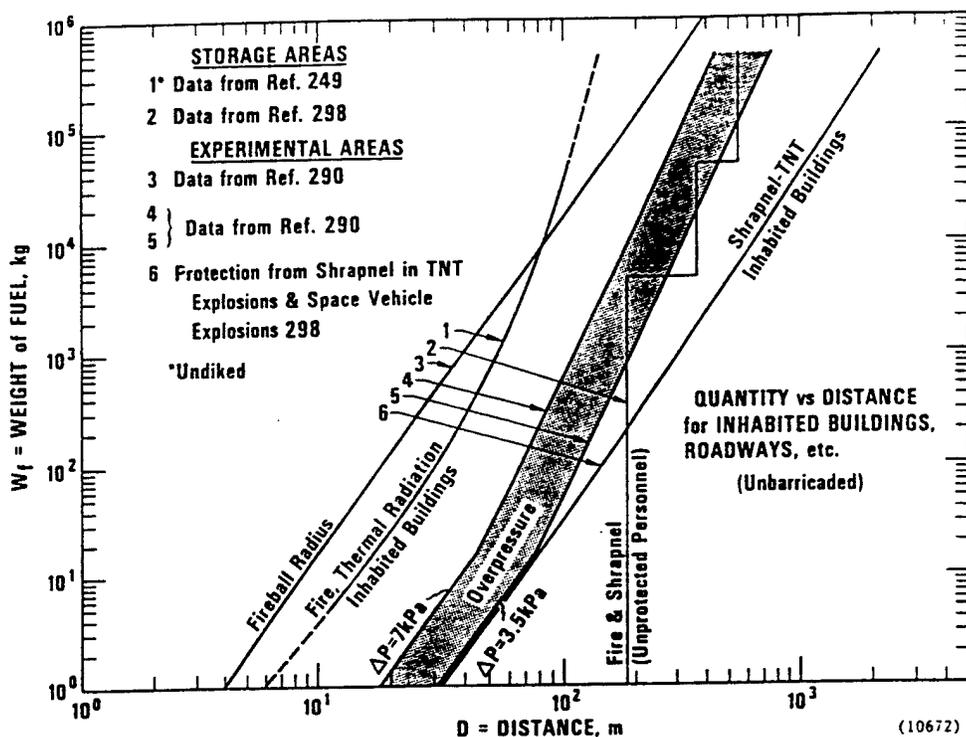

Figure 8.   Quantity-distance relationships for the protection of personnel near liquid hydrogen storage and experimental areas (unbarricaded).

We suggest that the installation be divided into three functional components for operational safety and to take advantage of the different criteria:

(a) a storage containing the minimum amount of hydrogen that commercial suppliers will deliver, typically 3000 kg,

(b) a run supply dewar with a built-in heat exchanger, typically 100 to 500 kg, and

(c) a closed-loop pressurized flow and test unit with a circulating pump and containing no more than 10 or 20 kg of hydrogen.

This separates functions and has the lowest quantity of material associated with the more hazardous functions and vice versa.

If safety authorities at WPAFB accept Figure 9, as 25 m safety distance can be applied to a 20 kg (280 liter) experiment, which would allow a 50 kW test of 3 minute duration.
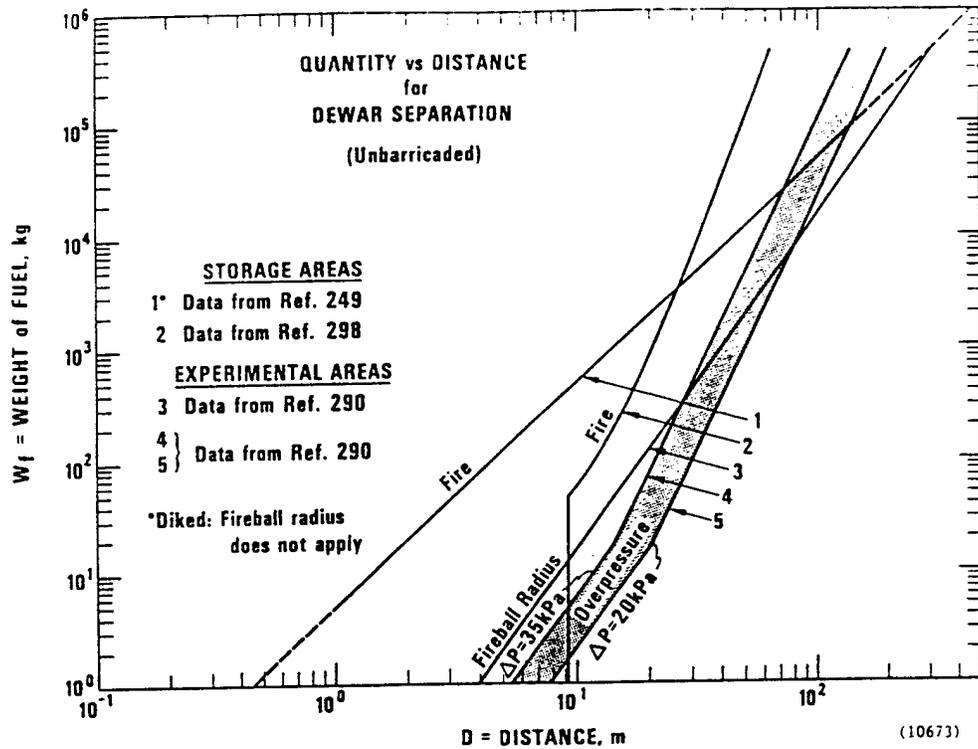
Figure 9.   Quantity-distance relationships for liquid hydrogen dewar separations in storage and experimental areas (unbarricaded).
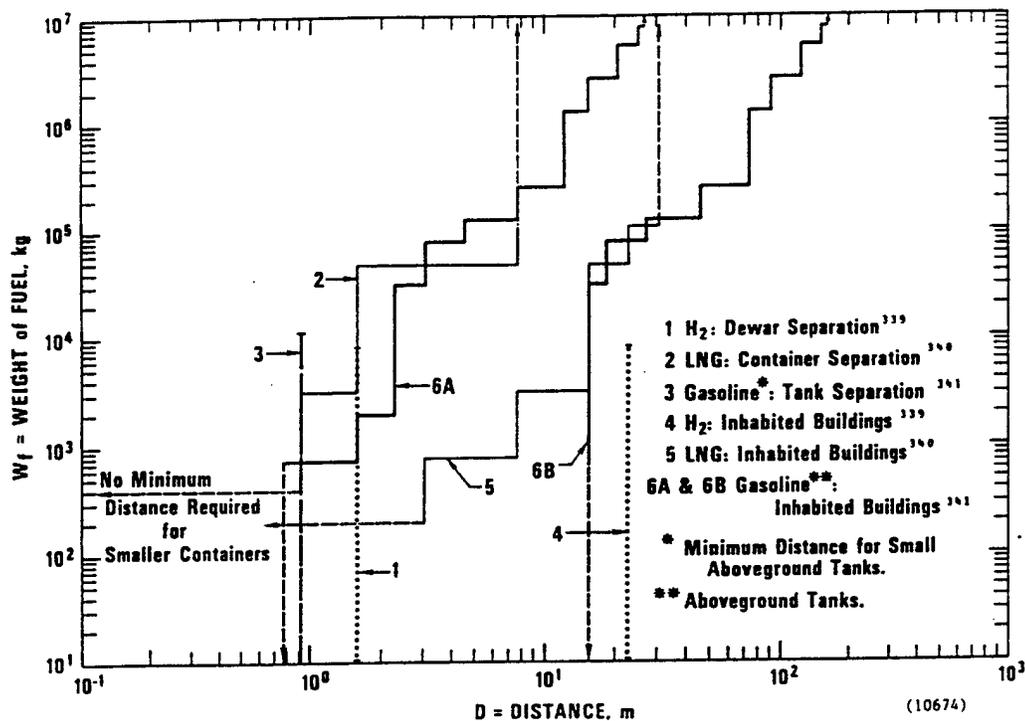

Figure 10.   Industrial storage standards (quantity-distance) for hydrogen, liquefied natural gas (LNG), and gasoline.

SECTION 5
CONCLUSIONS

We conclude that power conditioning systems can be cooled to 20 K with no mass penalty. Most components will be lighter and more efficient when cooled to 20 K.

Very few components have been tested at 20 K, however, and virtually no components have been designed specifically to operate at 20 K. The design data to design components and systems for 20 K operation is nonexistent.

In summary, technology development is needed for every component and for systems. The limited analysis and experimentation done to date shows that power conditioning systems can be cooled. The knowledge base, however, is insufficient to design systems or components.

SECTION 6

RECOMMENDATIONS

We recommend technology development of cryogenic power conditioning systems. The first step is to analyze and define missions. The second step is system trades and analysis to determine which systems can be expected to perform best at cryogenic temperatures. The third step is to assess the current technology. Finally, a plan should be made to direct the needed technology development. Technology development can then be started in areas where the needs and rewards are greatest.